

## Response to T. Reid, Referee #1

Dear Dr. Reid,

Thank you for your helpful review of our manuscript. We made all the grammatical and typesetting corrections you suggested in the manuscript. We also greatly expanded and better organized the methods section, to further clarify the model code, physics and parameterizations. Please find our responses to your other comments (bold) below, along with the relevant amendments to the manuscript text.

We have addressed the referee comments to the best of our abilities, with helpful improvements to the CMB model that did not alter the core findings and results of the discussion paper. However, please note that during the review process we also fixed an important error in the ice melt calculation within the debris layer. Formerly, the debris porosity was not taken into account. Now, the melt amount,  $M_d$ , in each 1-cm saturated debris layer when the temperature exceeds the melting point is given by

$$M_d = \frac{1}{L_F} (\phi \Delta T \rho_{ice} c_{ice} \Delta z) \quad (1)$$

where  $L_F$  is the enthalpy of fusion of ice,  $\phi$  is the porosity of the layer,  $\Delta T = (T_d - 273.15)$  is the excess temperature of the layer, and  $\Delta z = 1$  cm. Fixing this error affected the behaviour of the model during the transition season of fall 2011. As the debris ice melts more slowly, the debris temperature in basal saturated layers is constrained to the melting point for longer. Therefore, surface vapour fluxes do not compensate for decreased sub-debris ice melt during the fall period, although for summer 2011 that finding remains intact. The changes to the abstract and Sect 3.3 of the results are included at the end of this document after our response.

Best regards,  
Emily Collier & co-authors

**p1597, line 2: ‘a minimum debris water content of 2 kg m<sup>-2</sup>’ – I’d like more detail on why this figure was chosen. What field measurements were taken, and how?**

The value of 2 kg m<sup>-2</sup> is the amount of water required to saturate the lowest 1-cm layer in the debris given its porosity of 20%. The value was chosen as a first guess, since field measurements were not available and, in general, debris water contents are poorly constrained. Since we do not explicitly represent the actual processes that transport moisture into and within the debris (i.e., percolation, capillarity and water flow in response to hydraulic gradients), the minimum water content provides a small “source” term for debris moisture. The value of 2 kg m<sup>-2</sup> gives a volumetric water content of ~ 0.01, which is in agreement with empirically derived residual water contents of soils composed of more than 10% of “large” gravel clasts (5-10 mm in size;  $\theta_w \sim 0.00$  to 0.03; Wang et al. 2013).

Amended page 1597, line 1 to:

*“In addition, when the ice-debris interface reaches the melting point, a minimum debris water content is imposed to reflect field observations of a basal saturated layer during the ablation season (e.g., Nakawo and Young, 1981; Conway and Rasmussen, 2000; Kayastha et al., 2000; Reznichenko et al., 2010; Nicholson and Benn, 2012). As the water content of glacier debris cover is poorly constrained and no measurements are available, the minimum value is set to the amount of water needed to saturate the lowest layer in the debris, given its porosity and ice content.”*

Appended to the paragraph on porosity in Sect. 2.3:

*The porosity value of 20% in the lowest 1-cm layer in the debris gives a minimum water content of 2 kg m<sup>-2</sup> that is imposed only when the sub-debris ice is at the melting point. Sub-debris ice melt changes by ±1.8% if the minimum value is removed or doubled in the 2008 simulation.*

**Eq. 5 and related text: This is an interesting approach for estimating surface vapour pressure. However I feel it needs a more firm justification here in terms of theory and/or data. Is the linear relationship backed up by any field measurements, or theory e.g. from soil science or other fields?**

A widely used approach in the soil sciences to estimate the actual vapour pressure within the pore space is the thermodynamic relationship of Edlefsen and Anderson (1943) (e.g., Wilson et al. 1994; Karra et al. 2014), wherein the relative humidity is expressed as an exponential function of the pore liquid pressure. The solution for liquid pressure is computed for each grid cell in the computational domain (S. Karra, personal communication, May 2014). However, since the CMB model is missing many physical processes (e.g., capillary action, water vapour diffusion, instantaneous infiltration), this formulation would provide zero vapour pressure in the pore space above the saturated horizon.

We tested two additional approaches: (1) computing the saturation vapour pressure at the saturated horizon and (2) using an exponential relationship. The first approach produced a very small latent heat flux, since the saturated horizon is mainly located near the base of the debris and therefore temperature fluctuations are constrained by the proximity to the underlying ice. The second approach was implemented as follows

$$e_{sfc} = e_{sfc\_sat} \exp\left(\frac{-\theta_{air}}{\phi_{bulk}}\right)$$

where  $\theta_{air}$  is the void fraction of the bulk layer that is occupied by air and  $\phi_{bulk}$  is the bulk porosity (please see the following response for the calculation of these terms). However, this produced an excess of condensation and changed QL from an energy sink to a source, on average.

Therefore, the estimate of the surface vapour pressure when debris is exposed at the surface represents an important source of uncertainty. The approach we adopted in the manuscript is not consistent with conventional approaches employed in the unsaturated soil science literature. However, such approaches are often based on studies of finer texture material than glacier debris cover (e.g., as coarse as fine gravel, with a grain size of 2-5 mm). Furthermore, their implementation often requires empirical relationships based on extensive laboratory data (for example, to convert the soil water content to a variable that can be used in the Edlefsen and Anderson (1943) approach). Such studies are absent for glacier debris cover.

We feel that the simplified approach adopted in this paper, while perhaps not best suited for a detailed examination of moisture distribution within the debris, compares favorably to the available field data and is appropriate for our intended future research goals in the absence of more detailed evaluation data. There is also some support for a linear treatment in coarser grain soil, as Yeh et al. 2008 found that the effective degree of saturation in sand decreased approximately linearly in the top two meters above the water table.

Based on this comment, we added three paragraphs to the discussion section, about the uncertainty in the surface vapour pressure and missing physical processes in CMB-RES:  
*“The simulated QL and surface vapour fluxes depend on the estimate of the surface vapour*

pressure, which is an important source of uncertainty in the CMB-RES model. In unsaturated soil sciences, the relative humidity is often treated as an exponential function of the liquid water pressure in the pore space using the thermodynamic relationship of Edelfsen and Anderson (1943) (e.g. Wilson et al. 1994; Karra et al. 2014). However, testing an exponential relationship with the moisture content of the debris in CMB-RES resulted in strong in QL (MD = 28; MAD = 96  $W m^{-2}$ ) and a shift from QL as an energy sink to a gain, which was inconsistent with the EC data. For simplicity, we employed a linear approach, and there may be some support for this treatment in coarser texture soil, as Yeh et al. (2008) found that the effective degree of saturation in sand decreased approximately linearly in the top two meters above the water table.

In reality, water vapour fluxes occur at the saturated horizon, either at the surface or within the debris layer. However, in the 2008 simulation, the mean depth of the saturated horizon was 21.5 cm, where the proximity of glacier ice damped temperature fluctuations and constrained the mean temperature to ~275 K. Therefore, computing vapour fluxes at this level produced a very small latent heat flux, of -3.1  $W m^{-2}$  on average, that was also not in agreement with the EC data. CMB-RES likely provides an underestimate of the simulated location of the saturated horizon, since capillary action was not taken into account. For fine gravel soils (grain size of 2–5 mm), capillary rise is on the order of a few cm (Lohman 1972), while for coarser, poorly sorted glacier debris, the effect may be smaller. Underestimation of the height of the saturated horizon, and therefore of both the debris temperature and the saturation vapour pressure, is consistent with the small latent heat flux when vapour fluxes are computed at this level. As a part of future work, there is a need to accurately compute the vapour fluxes at the level of the saturated horizon.

In addition to neglecting capillary action, CMB-RES also does not account for many internal physical processes that have been highlighted in unsaturated soil sciences, including water vapour flow due to gradients in concentration and temperature; liquid water flow in response to hydraulic gradients; volume changes due to changes in the degree of saturation (e.g. Sheng 2011); deposition of water vapour and its contribution to the formation of thin ice lenses (e.g. Karra et al. 2014); and heat or moisture advection as a result of airflow (e.g. Zeng et al. 2011). However, incorporation of these processes into CMB-RES is currently limited by a lack of appropriate evaluation data. Instead, we focus on including processes related to phase changes, which have been demonstrated to have an impact on the subsurface temperature field and ablation rate (Reznichenko et al. 2010; Nicholson and Benn 2013). As a part of future work, CMB-RES could be improved by distinguishing the location of debris ice and water separately within saturated layers, thus potentially improving the simulated debris temperature profiles as the melting point constraint would only be applied to saturated layers containing ice.”

**It seems that using the fractional fullness of the reservoir (F\_res) might not be appropriate for layers of different thickness. E.g. a 1m layer with F\_res=0.6 would have a distance of 40cm between the top of the reservoir and the debris surface, whereas in a 10cm layer with the same F\_res it would only be 4cm away. Wouldn't the reservoir then have a much bigger effect on the surface vapour pressure in the thinner debris layer? It seems to me that debris thickness should be included in the equation and not just F\_res.**

Excellent point. To address this issue, we replaced  $F_{res}$  in Eq. 5 as follows,

$$e_{sfc} = e_{sfc}^* + \left( e_{sfc sat} - e_{sfc}^* \right) \cdot \left( 1 - \frac{\theta_{air}}{\phi_{bulk}} \right)$$

where  $\theta_{air}$  is the void fraction of the bulk layer that is occupied by air, given by

$$\theta_{air} = \sum_{i=1}^{m_K-1} \frac{\phi_i}{N}$$

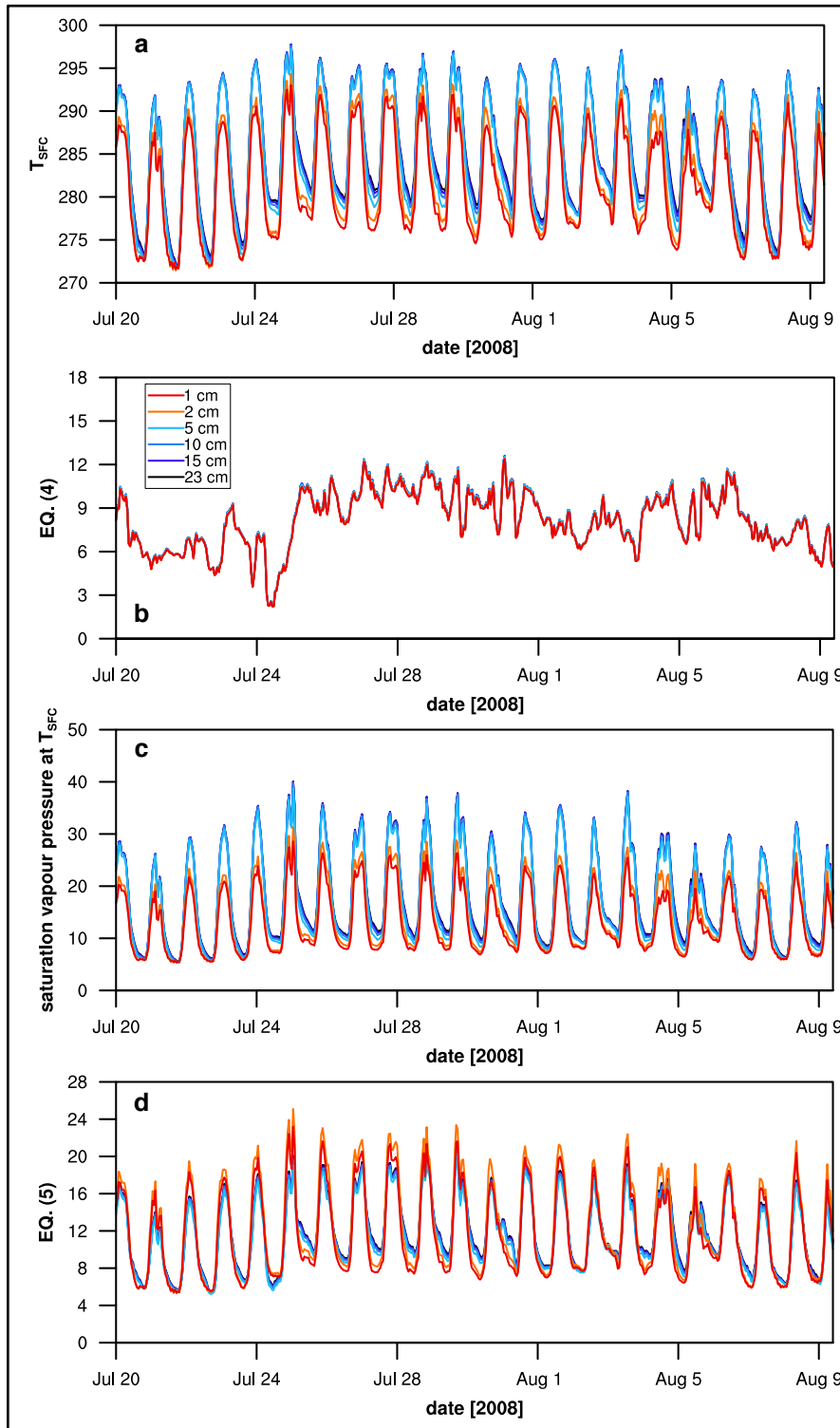
where  $m_K$  is the level of the saturated horizon and  $N$  is the total number of layers in the debris.  $\phi_{bulk}$  is the total bulk porosity, given by

$$\phi_{bulk} = \sum_{i=1}^{i=N} \frac{\phi_i}{N}$$

which is invariant under different debris thicknesses, due to the linear specification of the debris porosity. When the debris is completely unsaturated,  $\theta_{air} = \phi_{air} = 0.3$ , and when the saturated horizon reaches the upper layer,  $\theta_{air} = 0$ . Here we assume that  $\theta_{air}$  is a suitable representation of the changing distance from the height of the saturated horizon in the debris to the surface.

To illustrate the influence of this correction factor for varying debris thickness, we re-ran the 2008 CMB-RES simulation with debris thicknesses of 23, 15, 10, 5, 2 and 1 cm, and artificially set the debris water (ice) content to 50% (0%) of its capacity at each time step. Below is a figure showing time series of (a) debris surface temperature  $T_{sfc}$  [K], (b) the result of Eq. 4 [hPa], (c) the saturation vapour pressure at  $T_{sfc}$  [hPa], and (d) the result of Eq. (5), namely the final surface vapour pressure used in the CMB-RES model [hPa].

As one would expect, a water content of 50% produces a larger surface vapour pressure during the day in thinner debris layers compared with thicker ones, despite the higher surface temperatures and therefore saturation vapour pressure of thicker debris layers. The text of the manuscript has been updated to reflect these changes.



p1600, line 16-18: I have some data from a thermistor profile that might back up this model finding, I'll be in touch separately.

After careful consideration, we changed the approach used to prognose the glacier surface temperature. The eventual goal of this research is to couple the debris model with a high-resolution atmospheric model. For that application, determining an appropriate representative-surface-layer depth with time evolving snow cover is computationally expensive and impractical over large model domains. Therefore, we decided to follow the approach adopted in previous studies, in which the surface temperature is calculated iteratively such that there is zero residual energy in the surface energy balance equation (Eqn 1; e.g., Nicholson and Benn, 2006; Reid and Brock, 2010; Reid et al., 2012; Zhang et al. 2011). The results do not differ significantly from the previous approach, however the model is now more widely applicable.

Page 1595, paragraph 3 has been replaced with:

*“Consistent with previous modelling studies of debris-covered glaciers (Nicholson and Benn 2006; Reid and Brock 2010; Reid et al. 2012; Zhang et al. 2011), the model employs an iterative approach to prognosing surface temperature, with the solution yielding zero residual in the surface energy balance (Eq. 1). The model employs the Newton-Raphson method to calculate  $T_{SFC}$  at each time step as implemented in Reid and Brock (2010), with a different termination criteria of  $|F_{NET}| < 1E - 3$ . When snow or ice are exposed at the surface, the resulting  $T_{SFC}$  is reset to the melting point if it exceeds this value, and energy balance closure is achieved by using the residual energy for surface melt.*

Page 1600, paragraph 2 (which gave further details about the former approach for the Miage glacier) has been removed.

**p1600, line 20: I've never tried to measure this, but 60% porosity seems very high for the piles of clasts I've seen on Miage! If I were to guess I'd have said it couldn't be more than 40%, definitely not more than 50% because surely that would defy some mathematical stacking laws (and I don't think the clasts themselves are very porous)? I'd like to see more detail on how the authors made these measurements to justify such a high number, and if indeed it is too high then they could do a small sensitivity analysis to see how it affects their final numbers on mass balance.**

As we needed to re-run the simulations to address the comment on the estimation of the surface vapour pressure, we decided to change the upper bound on the porosity to 40%. While measurements indicated porosity values up to 60% (Brock et al. 2006), using the range of 20–40% gave better agreement in the bulk porosity value with measurements reported by Nicholson and Benn (2012) for other debris covers. While the actual amount of sub-debris ice ablation is sensitive to the choice of porosity range, the model behaviour and main findings presented in the paper are unaffected.

Amended p1600, paragraph 3 to read:

*“For both CMB-DRY and CMB-RES, we assumed that the debris porosity is a linear function of depth in the debris, decreasing from 40% at the surface down to 20% at the debris-ice interface. A range of 19 – 60% percent void space by volume was measured on the Miage glacier, by placing a known volume of surface debris in a graduated bucket and measuring the volume of water required to fill the air spaces (Brock et al. 2006). For this study, we used an upper-bound of 40%, such that the bulk porosity (30%) was consistent with other reported values for glacier debris (Nicholson and Benn 2012). A sensitivity study using the measured upper bound of 60% showed that while sub-debris ice melt was strongly affected (it decreased by ~17% in both simulations), the CMB model behaviour and the main results presented in Sect. 3 remained intact.*

**p1602, line 15: Should it say 'source' rather than 'sink' for QPRC? (I suppose this depends on whether air or surface temperature is higher?)**

We think sink is correct here. On average, QPRC is  $\sim -17 \text{ W m}^{-2}$  in the CMB models during daytime rainfall events, i.e. the surface temperature is higher. During nighttime rainfall, QPRC has a mean value of  $\sim +2 \text{ W m}^{-2}$ .

**Table 1: A third column showing some sources for these numbers would be nice.**

The column mainly pays homage to Brock et al. (2010), but done.

**Fig. 3b: It's not clear if the line for the first period (modelled wind speed I presume) is grey or black. Also the caption would benefit from an explanation that this was modelled from ERA.**

We changed the line color to green for the ERA data, reduced the line thickness to make the plots clearer, and amended the legend to say "ERA Interim (temporally downscaled)."

**Fig. 6b&10b: I'm curious as to how deposition is modelled? This isn't mentioned in the text and it could benefit from a sentence or two.**

Page 1594, line 7 added: *Surface vapour fluxes ( $Q_v$ ; i.e., sublimation or deposition [ $\text{kg m}^{-2}$ ], depending on the sign of  $QL$ ) at each time step  $\Delta t$  are calculated according to*

$$M_v = \frac{QL \Delta t}{L_H}$$

*where  $L_H$  is the latent heat of sublimation ( $2.84 \times 10^6 \text{ J kg}^{-1}$ ) or vapourization ( $2.51 \times 10^6 \text{ J kg}^{-1}$ ), depending on the surface temperature.*

**Fig. 8a-c: Would these look more intuitive with flipped axes?**

The plot of specific heat capacity is a bit squished, but it is more intuitive and consistent with previous figures.

**Fig. 9b is an excellent illustration of how moisture cools the debris. I wonder if you could make the colour scale a bit wider so that the small differences are highlighted better?**

We changed the shading for panel b, as well as moved and inverted the sign of the  $QL$  curve, since it obstructed the difference plot.

**Fig. 11: No units on y axes. I like this figure as a demonstration of refreeze, but it is quite difficult to understand – I think it would benefit from showing the full CMB-DRY temperature profile, as well as CMB-RES and the difference between the two.**

We added the units and an additional panel showing the full CMB-DRY temperature profile.

**Please give a detailed explanation of what happens to precipitation in CMB-DRY.**

Added on page 1596, line 27: *"For CMB-DRY, rainfall or other liquids water inputs are instantaneously removed as runoff from the debris layer and do not accumulate or contribute to vapour exchange between the debris and the atmosphere, similar to previous modelling studies (e.g., Reid and Brock 2010; Lejeune et al. 2013)."*

**I'd like a more detailed explanation of how mass balance is calculated, taking into account these three factors:**

- Mass gain due to debris being wet and thus lowering sub-debris ice melt
- Mass loss due to vapour fluxes at surface
- Mass gain due to precipitation

For the first factor, debris moisture in CMB-RES reduces the effective thermal diffusivity, resulting in less heat transfer to the underlying ice and therefore less melt, rather than a mass gain. We hope that this result is explained sufficiently on the last paragraph of page 1603.

To clarify the other two factors, we added a separate section about the mass balance calculation to the methods section (see below). Given that liquid precipitation is neglected in CMB-DRY and not accounted for in the accumulated mass balance calculation of CMB-RES, it is consistent that the mass balance of CMB-DRY is less negative than CMB-RES, since QL is neglected.

*“The total mass balance calculation in CMB-DRY and CMB-RES accounts for the following mass fluxes [ $\text{kg m}^{-2}$ ] each time step: solid precipitation; surface and vertically integrated subsurface melt; meltwater refreeze and formation of superimposed ice in the snowpack; changes in liquid water storage in the snowpack; and surface vapour fluxes. The contribution of surface vapour fluxes to or from the debris layer is zero when overlying snow cover is present and in CMB-DRY. In CMB-RES, these fluxes also contribute to changes in the debris water and ice content of the reservoir. For both models, sub-debris ice melt is calculated as the vertical integral of melt in the ice column underlying the debris.*

*Liquid precipitation contributes indirectly to the mass balance through changes in storage in the snowpack in both CMB models and directly in CMB-RES via reservoir storage. However, changes in the debris water and ice content in CMB-RES are not included in the mass balance calculation, so as to allow for a more direct comparison between CMB-RES and CMB-DRY of the influence of including the latent heat flux. The impact of changes in the storage of water and ice in the debris is quantified in Sect. 3. and has a negligible influence on the total accumulated mass balance.”*

## References

- Edlefsen, N.E., and Anderson, A.B.C.: Thermodynamics of soil moisture, *Hilgardia*, 15, 31-298, 1943.
- Wang, H., Xiao, B., Wang, M., and Shao, M.: Modelling the soil water retention curves of soil-gravel mixtures with regression method on the Loess Plateau of China, *PLOS One*, 8, DOI: 10.1371/journal.pone.0059475, 2013.



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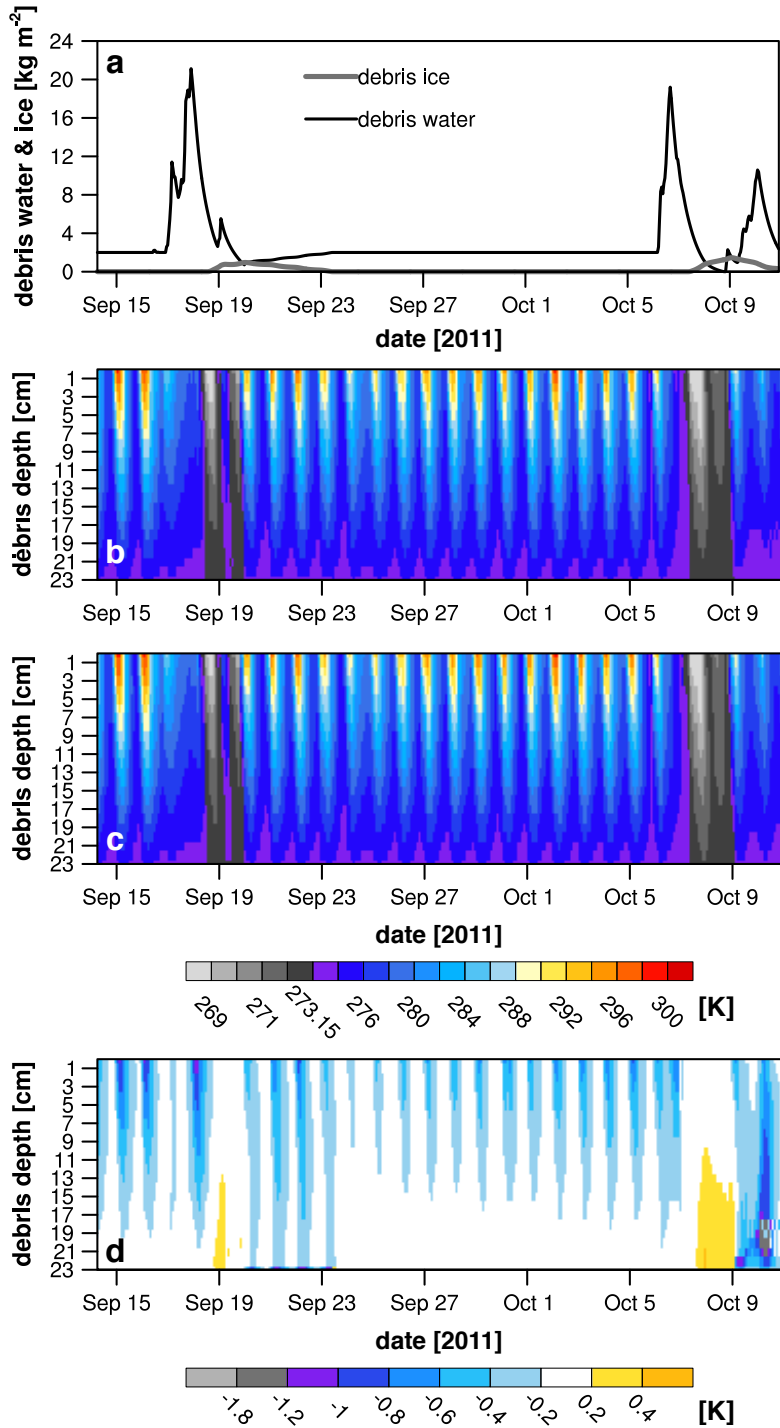
## Updated results for the transition season of fall 2011

Page 1590, line 18 (abstract): *“In combination with surface heat extraction by QL, sub-debris ice melt is reduced by 3.1% in 2008 and by 7.0% in 2011 when moisture effects are included. However, the influence of the parameterization on the total accumulated mass balance varies seasonally. In summer 2008, mass loss due to surface vapour fluxes more than compensated the reduction in ice melt, such that the total ablation increased by 4.0%. Conversely, in fall 2011, the modulation of basal debris temperature due to the presence of ice resulted in a decrease in total ablation, of 2.1%. Although the parameterization is a simplified representation of the moist physics of glacier debris, it is a novel attempt at including moisture in a numerical model of debris-covered glaciers and opens up additional avenues of future research.”*

Sect 3.3 has been amended to: *“Two freezing events occur during the 2011 simulation, between 18 September 23:00 LT–19 September 14:00 LT and between 7 October 9:00 LT--9 October 9:00 LT, at the tail end of two precipitation events with sub-zero air temperatures (cf. Fig. 4d). Net longwave and shortwave radiation are reduced, due to cooler surface temperatures and to small amounts of snowfall that increase the surface albedo (Fig. 10a). Rapid melt of the thin overlying snow cover (< 0.5 cm) and infiltration of rainfall at the beginning of the precipitation events provide the source water for refreeze in the debris (Figs. 10b and 11a). During the first event, a maximum of 1.0 kg m<sup>-2</sup> of ice is produced, which persists in the basal debris layer for a further three days after the last time step with refreeze. In the second event, the debris ice content reaches 1.4 kg m<sup>-2</sup>, and does not melt away before the end of the simulation.*

*The bulk presence of liquid water and ice in the debris layer influences the vertical temperature profile in two competing ways (Fig. 11b-d). Latent heat release due to refreezing warms the subsurface, on average by 0.3K but exceeding 0.7K for the hourly time steps with the greatest refreeze. However, the presence of ice in saturated basal layers constrains the debris temperature to the melting point. In combination with a reduction in the effective thermal diffusivity of saturated layers, the modulation of debris temperature results in a decrease in sub-debris ice melt of 7.0% in CMB-RES compared with CMB-DRY.*

*The accumulated mass balance between 14 September--11 October 2011 is -172.4 kg m<sup>-2</sup> for CMB-DRY and -168.8 kg m<sup>-2</sup> for CMB-RES. Changes in water and ice storage again have a negligible impact on simulated mass balance, resulting in a further ablation of 0.2 kg m<sup>-2</sup>. Thus, for the fall transition season, surface vapour fluxes do not compensate for the reduction in sub-debris ice melt due to the thermodynamic influence of ice in the debris. However, considering the same summer period in 2011 as in 2008 (20 July--11 August), the percent changes in accumulated mass balance and sub-debris ice melt are +4.0% and -3.2%, respectively, consistent with the findings of the 2008 simulation. Therefore, the influence of the reservoir parameterization varies seasonally.”*



**Figure 11:** (a) Time series from the 2011 simulation of the debris water (black line) and ice (grey line) content [ $\text{kg m}^{-2}$ ]. Temporal and depth variation of the debris temperatures in (b) CMB-RES and (c) CMB-DRY, and (d) the difference between the model runs (CMB-RES minus CMB-DRY). Units are K.